

The Phase-Induced Amplitude Apodization Coronagraph

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ABSTRACT

The Phase-Induced Amplitude Apodization Coronagraph (PIAAC) uses lossless amplitude apodization (performed by reflection on aspheric mirrors) to produce a high contrast stellar PSF.

It combines nearly 100% throughput with small inner working angle ($<2 \lambda/D$), preserves the angular resolution of the telescope, is sufficiently robust to stellar angular size and can be designed to have very good achromaticity. The theoretical performance of the PIAAC would enable TPF-C science with a telescope half the size of what would be required if a coronagraph utilizing conventional apodization were used.

In this paper, we show how the PIAAC functions and what is its expected performance. We also discuss PIAA optics manufacturing challenges, design trade-offs and results from our ongoing laboratory demonstration.

PIAAC PRINCIPLE

Conventional apodization coronagraphs use masks to apodize the telescope pupil. These masks unfortunately remove most of the planet light and greatly reduce the telescope angular resolution.

An alternative solution is to produce the apodized pupil by geometrical redistribution (remapping) of the flux in the pupil plane rather than selective absorption. The PIAAC performs this lossless amplitude apodization with 2 aspheric optics; the resulting pupil is then yields a high contrast PSF in which starlight can be removed by a small focal plane occulting disk.

The geometric remapping introduced by the aspheric PIAA mirrors limits the “clean” field of view in the focal plane: PSFs for sources at more than $\sim 10 \lambda/D$ from the optical axis are heavily distorted, which has the undesirable effect of mixing more exozodiacal+zodiacal light with the planet image. A set of correcting optics may be added after the focal plane occulter to restore a clean PSF across a reasonable field of view (up to $100 \lambda/D$ in radius).

A schematic representation of the PIAAC is shown in Figure 1, which also shows off-axis PSFs in both the “intermediate” focal plane (where the focal plane occulter is located) and the final focal plane (where field of view is restored).

EXPECTED PERFORMANCE

The PIAAC coronagraph performance is quantified and compared with other coronagraphs in the “Theoretical analysis of coronagraphs” paper in this volume. We summarize here the main characteristics of the coronagraph:

- **nearly 100% throughput** (see section “Design trade-offs: (2) Mild pupil apodization with conventional apodizer”)
- $1\lambda/D$ angular resolution
- $<2 \lambda/D$ IWA
- full 360 deg search area
- **good achromaticity** (see section “Design trade-offs: (2) Mild pupil apodization with conventional apodizer”)

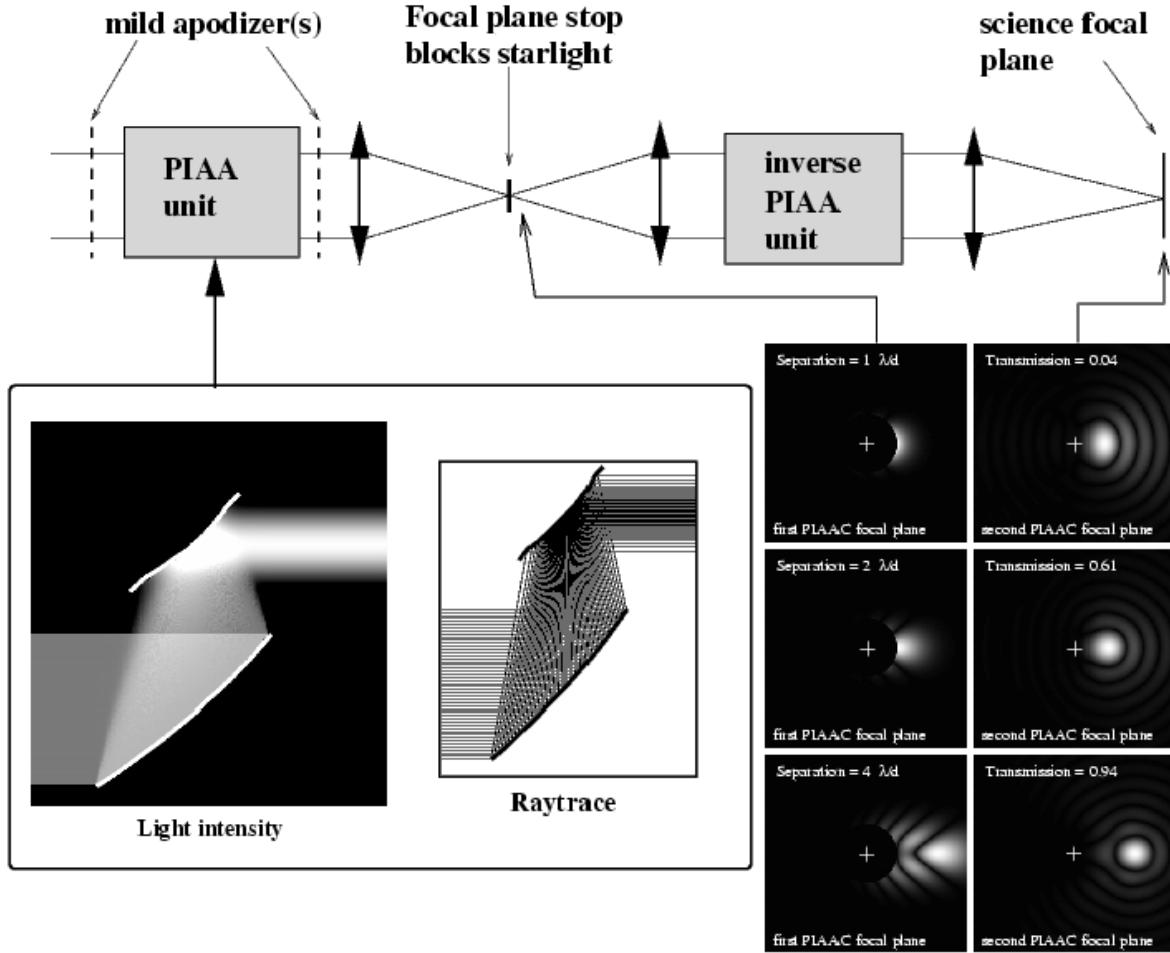


Figure 1: Schematic representation of the PIAAC. The telescope light beam enters from the left and is first apodized by the PIAA unit. Mild apodizer(s) are used to perform a small part of the apodizations, and are essential to mitigate chromatic diffraction propagation effects and to allow for the design of “friendly” aspheric PIAA mirrors. A high contrast image is then formed, allowing starlight to be removed by a small occulter. An inverse PIAA unit is required to “sharpen” the image of off-axis sources.

DESIGN TRADE-OFFS

(1) Focal plane occulter design and size

The PIAAC is a low-IWA coronagraph, and is therefore quite sensitive to low-order aberrations. Fortunately, this also means that low order aberrations can be efficiently and rapidly measured from the science focal plane.

For the PIAAC, as well as for any coronagraph with a focal plane occulter, the occulter should preferentially be reflective, so that the bright starlight can be used to measure low order aberrations before they start to impact science observations. We have designed such a mask, and further optimized the concept by only using the light falling within the $\sim 0.5 \lambda/D$ to $\sim 1.5\lambda/D$ radius interval to maximize its sensitivity (in this mask design, the very center of the mask is opaque out to $0.5 \lambda/D$, the mask is reflective from 0.5 to $1.5\lambda/D$ and transmissive outward of $1.5 \lambda/D$).

Thanks to this scheme, low-order aberrations can be measured to the required accuracy within a fraction of a second: the wavefront stability requirements for low order aberrations is therefore greatly relaxed.

(2) Mild pupil apodization with conventional apodizer

A PIAAC in which the apodization is performed entirely by the aspheric optics faces a very serious challenge: the outer edge of the first PIAA mirror (PIAA M1) has a small radius of curvature over a very small region. Since a large outer region of the output apodized beam contains a very small fraction of the total light in the pupil, the remapping needs to expand a very narrow annulus at the outer edge of PIAA M1 into a broad annulus on PIAA M2: this explains why the outer edge of PIAA M1 exhibits this sharp narrow “bend”. This brings 2 problems:

- PIAA M1 becomes very difficult to manufacture
- The very sharp feature at the edge of M1 creates unwanted diffraction effects which are unfortunately chromatic, and therefore reduce the spectral bandwidth over which the PIAAC can be used.

A solution to both problems is to share the apodization between a PIAA system and a mild apodizer at the output of the PIAA. Since the problem arises from the fact that the apodized pupil is very dark at its edges, it is solved by designing the PIAA to maintain the outer edge of the apodized beam at typically 1% of the surface brightness of the center of the beam. A mild apodizer then further reduces the flux in this already fairly dark part of the apodized beam. The conventional apodizer removes a small fraction of the total light (~10%) and has therefore a limited impact on the system throughput, IWA and angular resolution. A detailed analysis of this trade-off [Pluzhnik et al. 2006] shows that PIAA systems can be designed to be achromatic at the 1e- 10 level over the whole visible spectrum if one is willing to lose approximately 20% of the incoming light.

OPTICS MANUFACTURING

The PIAA optics are highly aspheric. The outer edge of PIAA M1 is the most challenging feature: it is strongly curved over a relatively small radius interval. With the PIAAC “hybrid” design described above (combination of PIAA apodization with a conventional apodizer), the PIAA optics shapes are within current manufacturing capabilities. High precision polishing of aspheric optics has been developed for extreme-UV lithography, and is now available from several vendors.

While each PIAA mirror can first be polished independently of the other (using a computer generated hologram—CGH—for null testing), the final step of fine polishing should aim to a flat wavefront in the 2-mirrors PIAA system.



Figure 2: PIAA M2 after diamond turning (prior to polishing)

The PIAA mirrors used in our laboratory demonstration (see next section) were polished by Axsys Technologies (MI, USA). The main fabrication steps are:

- diamond turning of an aluminum substrate
- Nickel coating of the aluminum parts
- Diamond turning of the nickel layer
- Hand polishing of each mirror against a CGH reference
- System assembly
- Fine hand polishing of one of the mirrors within the system to obtain a flat wavefront

The beam size was chosen to be large enough (75mm diameter) to accommodate the manufacturing process described above. The system wavefront obtained was 25nm RMS. Existing computer polishing and metrology processes would lead to significantly higher quality optics.

LABORATORY DEMONSTRATION

Our laboratory prototype includes a monochromatic light source (single mode fiber at HeNe), immediately followed by the 2 PIAA aspheric mirrors (which are designed for a f/15 diverging input beam and deliver a f/15 output converging beam). All optics (PIAA and reimaging optics) are within an enclosure which provides some

thermal stability. A 1024 actuators (32×32) MEMs-type actuators, driven by custom-built 16-bit high voltage drivers, is used to correct for residual wavefront aberrations. A phase diversity algorithm is used for wavefront control (the diversity is introduced by the DM itself). In the initial configuration of our experiment, no focal plane mask was blocking starlight, and the apodizer was not located in a pupil plane.

Despite these limitations, a $2.5e-6$ contrast was reached at $\sim 1.5 \lambda/D$ from the optical axis (see Fig. 3).

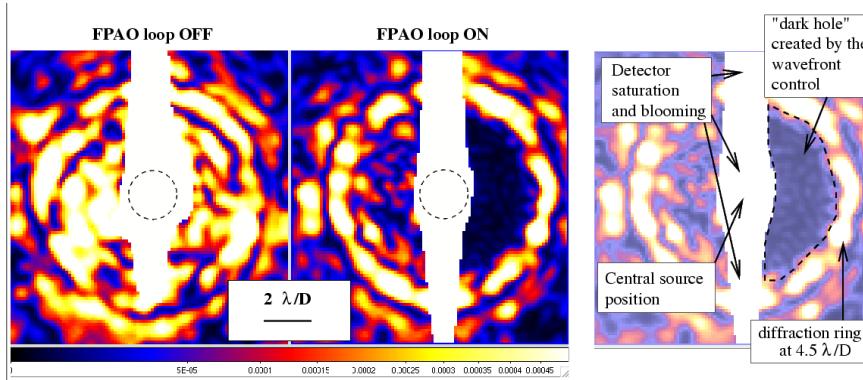


Figure 3: Preliminary results from the PIAA coronagraph laboratory demonstration. A heavily stretched version of our laboratory PSF image (left) shows that almost all starlight is concentrated within $1.5 \lambda/D$ radius (the large vertical structure is due to charge bleeding on the detector). The light beyond $1.5 \lambda/D$ is due to phase aberrations in the system and is greatly reduced thanks to wavefront correction using focal-plane Adaptive Optics (FPAO) as shown in the middle image. At the position of the first Airy ring, the contrast is $2.5e-6$. The large bright (1e-3 contrast) ring visible in the image is at 4 to 5 λ/D from the central star.

In the new optical layout (see Fig. 4), a pupil plane is made available for the conventional apodizer, and a focal plane is accessible for the focal plane occulter.

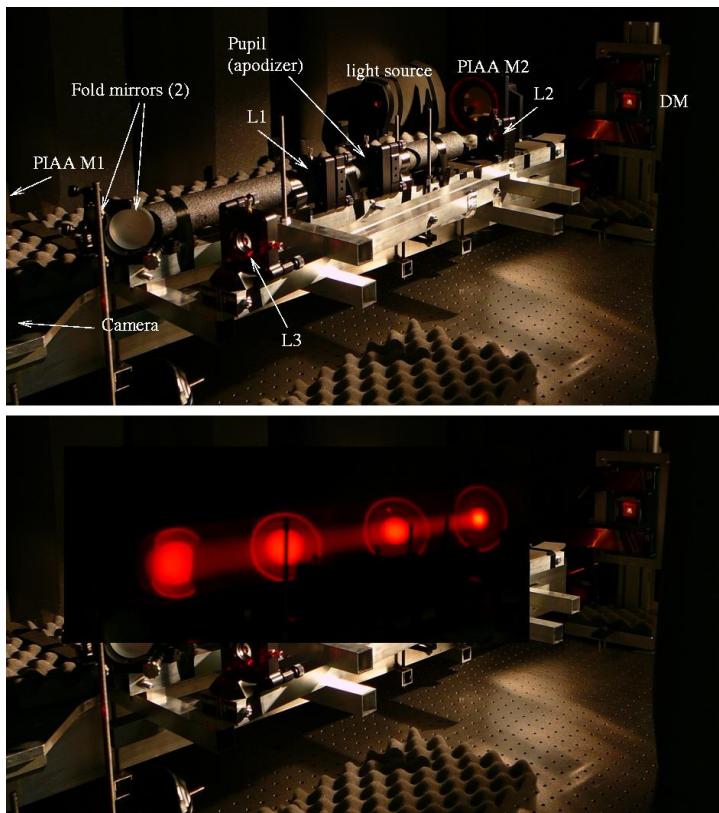


Figure 4: Layout of the PIAA laboratory experiment. In the bottom panel, a long exposure acquired while moving a white screen reveals the beam apodization between PIAA M1 and PIAA M2.

CONCLUSIONS / FUTURE WORK & STUDIES

The PIAA coronagraph is theoretically very efficient, and could allow TPF-like science goals with a moderate size visible telescope (about 3m). Preliminary laboratory results have confirmed the basic principle and demonstrated high throughput, low IWA coronagraphy at the $\sim 1e-6$ contrast level. We are currently improving our laboratory testbed to reach higher contrast levels.

PIAA differs from more conventional coronagraphs in 2 aspects, which each deserve further study:

- PIAA has a lower IWA: low order aberrations need to be kept very low. This may require a dedicated low-order WFS using light reflected by the central occulter.
- PIAA remaps the wavefront, which has strong implications for the overall design of the wavefront control optics. Placement of the DM(s) within the optical train (before and/or after the PIAA optics?) is critical.

More information about PIAAC in the following papers:

"Diffraction-based Sensitivity Analysis of Apodized Pupil-mapping Systems", Belikov, Ruslan; Kasdin, N. Jeremy; Vanderbei, Robert J., 2006 ApJ, 652, 833

"Exoplanet Imaging with a Phase-induced Amplitude Apodization Coronagraph. III. Diffraction Effects and Coronagraph Design", Pluzhnik, Eugene A.; Guyon, Olivier; Ridgway, Stephen T.; Martinache, Frantz; Woodruff, Robert A.; Blain, Celia; Galicher, Raphael, 2006 ApJ, 644, 1246

"Diffraction Analysis of Two-dimensional Pupil Mapping for High-Contrast Imaging", Vanderbei, Robert J., 2006 ApJ, 636, 528

"Exoplanet Imaging with a Phase-induced Amplitude Apodization Coronograph. II. Performance", Martinache, Frantz; Guyon, Olivier; Pluzhnik, Eugene A.; Galicher, Raphael; Ridgway, Stephen T., 2006 ApJ, 639, 1129

"Pupil Mapping in Two Dimensions for High-Contrast Imaging", Vanderbei, Robert J.; Traub, Wesley A., 2005 ApJ, 626, 1079

"Laboratory Demonstration and Numerical Simulations of the Phase-Induced Amplitude Apodization", Galicher, Raphael; Guyon, Olivier; Otsubo, Masashi; Suto, Hiroshi; Ridgway, Stephen, 2005 PASP, 117, 411

"Exoplanet Imaging with a Phase-induced Amplitude Apodization Coronagraph. I. Principle", Guyon, Olivier; Pluzhnik, Eugene A.; Galicher, Raphael; Martinache, Frantz; Ridgway, Stephen T.; Woodruff, Robert A., 2005 ApJ, 622, 744

"Two-Mirror Apodization for High-Contrast Imaging", Traub, Wesley A.; Vanderbei, Robert J., 2003 ApJ, 599, 695

"Phase-induced amplitude apodization of telescope pupils for extrasolar terrestrial planet imaging", Guyon, Olivier, 2003 A&A, 404, 379

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